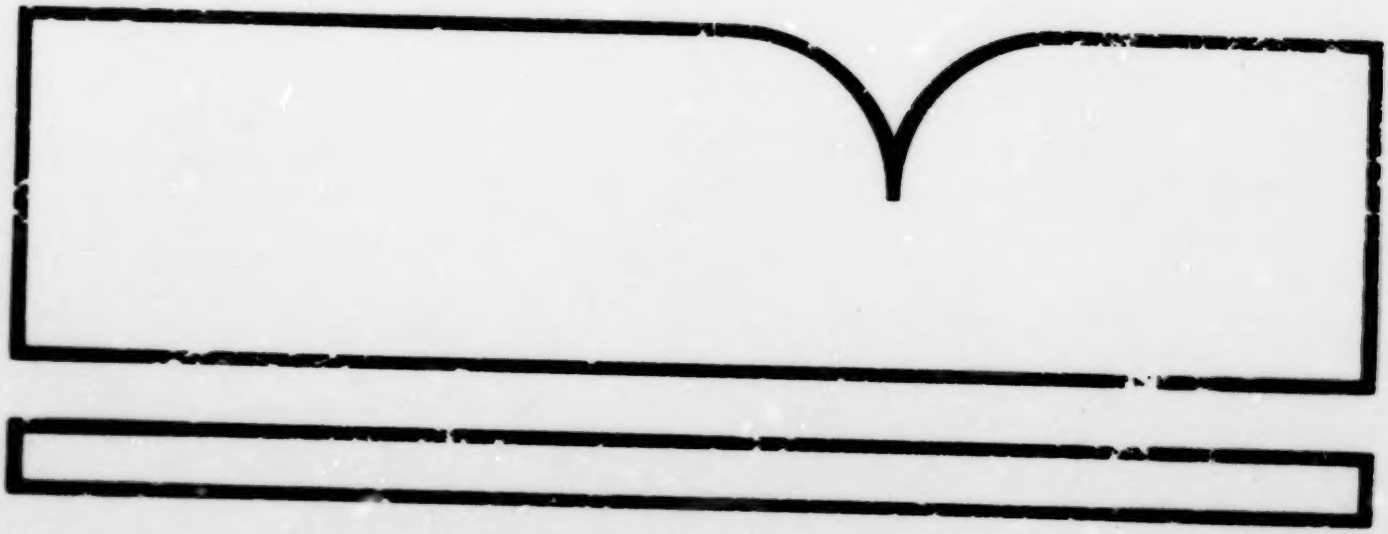
PB90-196585

# Role for a Geographical Information System in a Large Environmental Project

(U.S.) Corvallis Environmental Research Lab., OR

1989



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|---|---|
| 1. REPORT NO. EPA/600/J-89/307 | 2. |
| 3. R PB90-196585 | |
| 4. TITLE AND SUBTITLE The role for a Geographical Information System in a large environmental project | 5. REPORT DATE |
| | 6. PERFORMING ORGANIZATION CODE |
| 7. AUTHOR(S) W. G. Campbell, M. R. Church*, G. D. Bishop, D. C. Mortenson, and S. M. Pierson | 8. PERFORMING ORGANIZATION REPORT NO. |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS *U.S. EPA, ERL-Corvallis; all others, NSI, ERL-Corvallis, OR | 10. PROGRAM ELEMENT NO. |
| | 11. CONTRACT/GRANT NO. |
| 12. SPONSORING AGENCY NAME AND ADDRESS US Environmental Protection Agency Environmental Research Laboratory 200 SW 35th Street Corvallis, OR 97333 | 13. TYPE OF REPORT AND PERIOD COVERED Journal Article |
| | 14. SPONSORING AGENCY CODE EPA/600/2 |

15. SUPPLEMENTARY NOTES
1989. International Journal of Geographical Information Systems 3(4):349-362.

16. ABSTRACT

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17. KEY WORDS AND DOCUMENT ANALYSIS

| a. DESCRIPTORS | b. IDENTIFIERS/OPEN ENDED TERMS | c. COSATI Field/Group |
|---|---|---|
| | | |

| | | |
|---|---|---|
| 18. DISTRIBUTION STATEMENT Release to Public | 19. SECURITY CLASS (This Report) Unclassified | 21. NO. OF PAGES |
| | 20. SECURITY CLASS (This page) Unclassified | 22. PRICE |

EPA Form 2220-1 (9-73)

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SPRINGFIELD, VA. 22161

INT. J. GEOGRAPHICAL INFORMATION SYSTEMS, 1989, VOL. 3, NO. 4, 349–362

EPA/600/J-89/307

# The role for a geographical information system in a large environmental project

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**Abstract.** A geographical information system (GIS) has proved to be a valuable tool in the Direct/Delayed Response Project—a comprehensive examination of the future, long-term chemical response of surface waters to acidic deposition. The role of the GIS within the project includes aggregation, analysis and display of various forms, scales and projections of environmental data related to acidic deposition. The GIS is particularly valuable for effectively communicating key scientific findings and results of regional, national and international importance to a diverse audience.

## 1. Introduction

Geographical information system (GIS) technology has been applied to a wide variety of environmental problems. In the application described here, we use a GIS in a regional assessment of surface water acidification. This differs from many previous GIS applications in research into aquatic effects in that it represents a regional, extensive study rather than a site-specific, intensive application.

### 1.1. *The Direct/Delayed Response Project*

Much scientific interest and public debate surrounds the effects of 'acid rain' (correctly termed acidic deposition). A comprehensive chemical survey (the National Surface Water Survey (NSWS), Linthurst *et al.* 1986, Landers *et al.* 1988, Kaufmann *et al.* 1988) of the lakes and streams of the U.S.A. considered to be most vulnerable to acidic deposition (i.e., those with the lowest acid neutralizing capacity, or ANC) was recently completed by the U.S. Environmental Protection Agency (EPA). Analyses of the NSWS data, along with data on atmospheric deposition, clearly indicate that long-term deposition of sulphur-containing compounds (originating from the combustion of fossil fuels (Mohnen 1988)) has acidified some surface waters in the northeastern U.S. (Sullivan *et al.* 1988) and Ontario, Canada (Neary and Dillon 1988). Important questions remaining include whether additional adverse effects will occur, how extensive these effects might be, how rapidly the effects might occur and what levels of deposition might limit such effects.

To address these complex questions, the EPA has implemented the Direct/Delayed Response Project (DDRP) (Church 1989). The DDRP draws its name from the broad question of whether additional effects of acidic deposition might be immediate or

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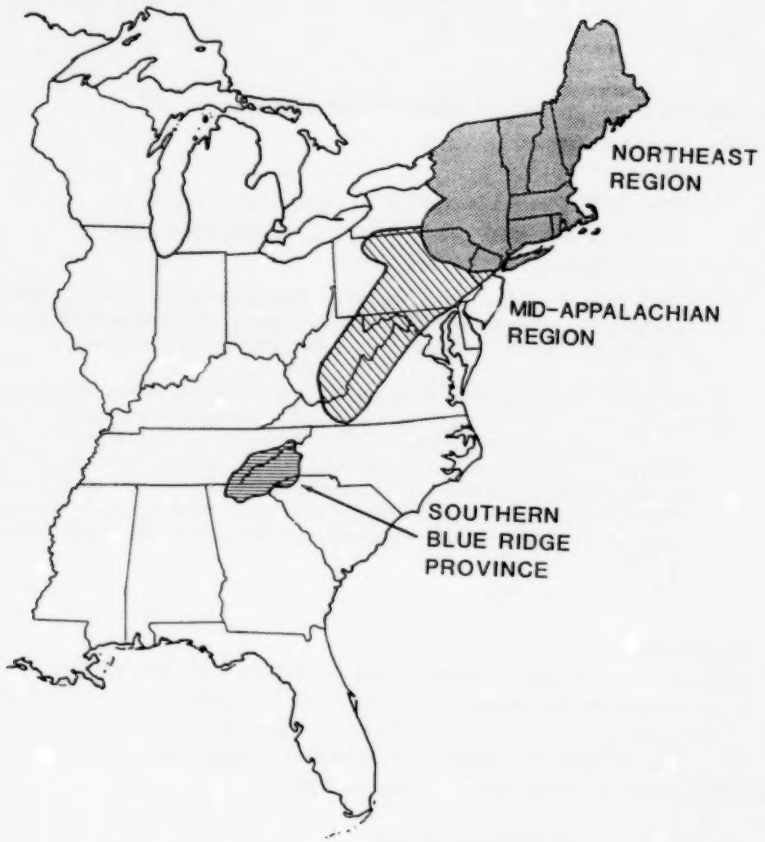


Figure 1. Direct/Delayed Response Project study regions.

immediately proportional to the levels of deposition (direct) or whether there are lags in time (delayed) related to important edaphic characteristics. The project is being conducted in three regions of the eastern U.S.A. where low ANC surface waters exist and where levels of atmospheric deposition are greatest. The three regions are the northeastern U.S.A., the upland regions of the Mid-Atlantic Region (termed here the Mid-Appalachian Region) and the mountainous section of the south-east, called the Southern Blue Ridge Province (SBRP) (figure 1).

### 1.2. *The DDRP approach*

The DDRP utilizes a regional top-down approach to assess the future chemical status of surface waters. This approach involves (1) defining the population at risk, (2) selecting a representative sample of watersheds, (3) characterizing these watersheds with regard to their response times to acidic deposition, and (4) extrapolating the results to the pre-defined target population. The primary advantage of this approach is that, by defining a target population and selecting a representative sample, we can extrapolate the results of our analyses from the sample to the population with a known level of certainty.

### 1.3. *The need for a GIS*

The DDRP addresses an exceedingly complex problem involving all facets of the biosphere. We perceived a GIS to be a unique tool for this type of regional environmental analysis because of its capability to perform various functions efficiently, including (1) data collection and verification, (2) analysis of spatial data and (3) communication of key scientific findings through the display of mapped information.

Because of the complexity of the processes affecting surface water acidification, the DDRP must rely on a wide variety of data sets ranging in scale from national to regional to watershed. For example, the potential acidification of a lake depends not only on edaphic and other terrestrial characteristics of the watershed, but also on regional patterns of atmospheric deposition. With a GIS, we are able to combine, aggregate, manage and display site-specific information (e.g., soil pedon information), watershed-level mapped data (e.g., soils) and regional data such as sulphur deposition.

The GIS also provides tools for spatial analysis of a variety of chemical variables, the results of modelling and other data important to the effects of acidic deposition. For example, the GIS can be used for displaying and interpreting the spatial trends of results obtained from physically-based acidification models.

Finally, the GIS can be used to produce efficiently mapped information based on DDRP analyses. These maps can be used to communicate results to the scientific community, to policy-oriented segments of the EPA, to members of the Legislative Branch of the U.S. Government, to state governments and their representatives and, ultimately, to a concerned public.

To acquire GIS capabilities, the DDRP purchased an ARC/INFO GIS (ESRI 1987) in March 1985. The GIS was installed on a Digital Equipment Corporation VAX 11/750 and was fully operational by October 1985. The GIS has since been re-installed on a VAX 785/8650 cluster, primarily because of a large increase in the required computer resources. Additional hardware includes two digitizing workstations, a Calcomp 5845 colour electrostatic plotter, a Calcomp 1075 four-pen plotter, and an ever-increasing number of alphanumeric and colour graphics terminals.

## 2. Data collection and verification

The GIS provides two unique functions related to data collection and verification. These functions are locational/logistical support and data entry and validation. Although these two functions are discussed separately, they both rely on the ability of a GIS to enter, aggregate, manage and display spatial information efficiently.

### 2.1. *Locational/logistical support*

In the north-east, 145 lake/watershed systems that were part of the National Lake Survey were selected for the DDRP (Linthurst *et al.* 1986, Landers *et al.* 1988). Lakes of low interest (ANC > 400 $\mu$eq/l, depth < 1·5 m, or culturally disturbed) were excluded as were watersheds greater than 3000 ha in size. In the SBRP, all watersheds less than 3000 ha that were part of the Pilot Phase of the National Stream Survey (Messer *et al.* 1986) were selected, resulting in a sample of 35 watersheds. In the Mid-Appalachian Region, all watersheds sampled in the National Stream Survey (NSS) (Kaufmann *et al.* 1988) were considered. First, streams of low interest (ANC > 200 $\mu$eq/l, affected by acid mine drainage, or culturally disturbed) were eliminated. Next, all remaining watersheds in the Southern Piedmont Region or Coastal Plain were eliminated from consideration because of our predominating interest in trout streams of the mountainous region.

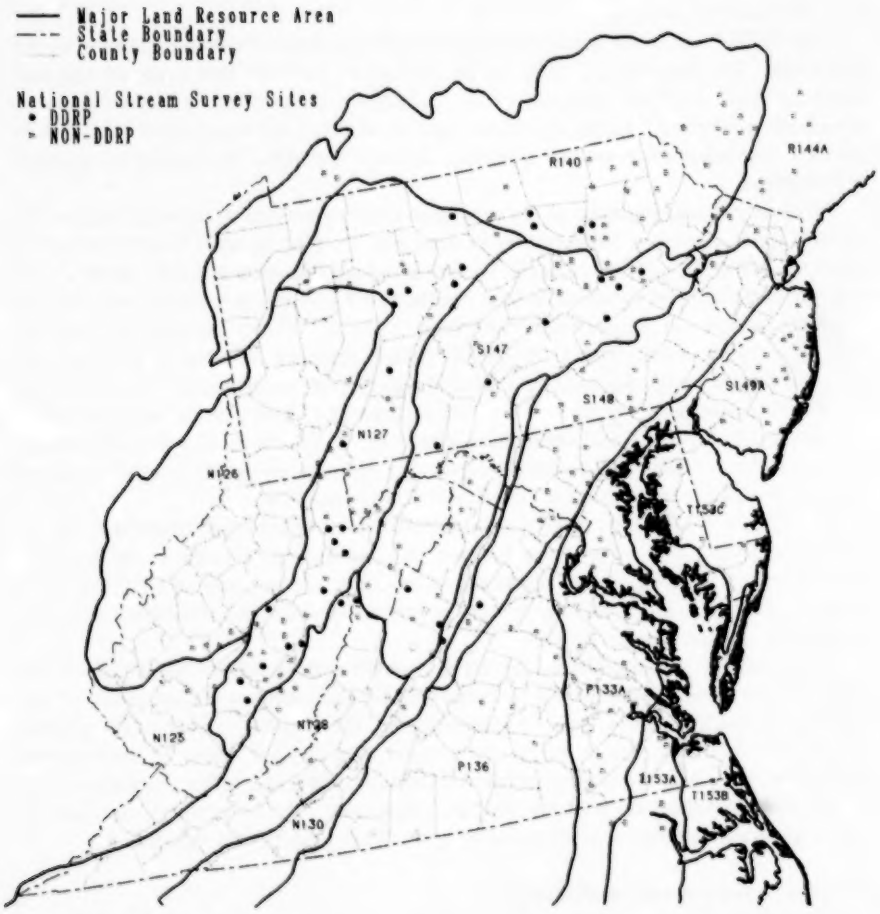


Figure 2. Site location map (with MLRA regions) of the Mid-Appalachian watersheds.

Watersheds clearly north of the maximum extent of glaciation were also eliminated from the Mid-Appalachian regional sample because of regional duplication (i.e., the DDRP Northeast Region covers the glaciated region of the northeastern U.S.A.). We determined sites to be eliminated by overlaying NSS site locations with digital Major Land Resource Area maps (MLRA (USDA 1981)). Selection in the Mid-Appalachian Region resulted in a total of 36 watersheds (figure 2).

The watersheds were then mapped for soils, vegetation, depth to bedrock and drainage by the U.S. Department of Agriculture (USDA) Soil Conservation Service

(Lee *et al.* 1989). In the Mid-Appalachian Region the mappers were aided by GIS-generated site location maps, depicting the sites with appropriate political boundaries (state and/or county lines) and MLRA designations (see figure 2). The site location maps were particularly useful for locating watersheds, scheduling mapping activities and budgeting resources. Following mapping, the manuscript maps were scanned for obvious problems or errors and either corrected in-house or returned to the mappers for resolution. The maps were then digitized into the GIS and the land area was summarized.

Following digitization, soil mapping units were re-aggregated throughout the DDRP regions into distinct soil sampling classes (Lee *et al.* 1989). Random pedon sites were then selected to characterize the individual sampling classes. Site selection for pedon sampling had three parts: random selection of watersheds, random selection of pre-determined sampling sites on soils maps and random selection of transect direction if the desired sampling class did not occur within a specified distance of the pre-selected site. The sites were then sampled for a variety of physical and chemical characteristics. Following sampling, the latitude and longitude of the selected site were recorded. To verify latitude and longitude, the sampling site locations were entered into the GIS and overlaid with GIS-generated soil maps. Each sample site was then compared with a physical descriptor of the sample site location, as recorded by the mappers (e.g., next to 'such-and-such' highway). Any discrepancies between the two estimates of sample site locations were noted and resolved. Final maps and data (e.g., latitude and longitude) for the sample sites were then generated.

### 2.2. *Data capture*

Existing mapped information was integrated with the digital watershed maps, including streams, geology, topography (in the form of digitized contours) and 1 : 250 000-scale digital elevation models (DEM). Blue-line stream lengths and contour (elevational) lines were digitized directly from 1 : 24 000 or 1 : 62 500 topographic maps. The digitized contour line represented the first 40′ contour above the level of each lake (the second 20′ contour for maps with 20′ contour intervals, the fourth 10′ contour for maps with 10′ contour intervals, etc.) within the watershed, bounded by the appropriate basin or sub-basin.

Bedrock geology was digitized directly from state geology maps. Because of the inherent problems in going from a small scale (1 : 250 000 or 1 : 500 000) to a large scale (1 : 24 000), watershed-specific detail was lost. The compromise, however, was a gain in regional consistency of legends, at least on a state-by-state basis. Although some predictive and explanatory power for individual watersheds will be lost, this consistency helps us to evaluate the role of regional-scale geology on surface water chemistry.

To provide input into a topographically-based, variable source area watershed model (TOPMODEL (Wolock *et al.* 1989)), 1 : 250 000-scale DEMs were incorporated into the mapped watershed database. Subsets of the DEM representing a block or elevational grid corresponding to the watershed were extracted and combined with estimates of permeability and depth to bedrock. TOPMODEL uses elevation and soils (including soil depth) to compute indices of soil–water contact time and flow-path partitioning. The results from TOPMODEL help to characterize the hydrological response characteristics of the watersheds. Systems that respond quickly to precipitation allow for fewer interactions between acidic deposition and edaphic

characteristics, whereas slower responding systems have more interactions and greater potential for acid neutralization.

Regional data have also been incorporated into the watershed database. Because of a lack of hydrological information (the watersheds were selected, not on the basis of the availability of gauging information, but randomly to characterize a region), watershed runoff was interpolated from (expert-drawn) runoff maps (Krug *et al.* 1988). The runoff maps were received in digital format, loaded into the GIS, overlaid with DDRP study sites and produced as hard copy. Based on runoff contours and expert opinion, runoff at the individual sites was estimated.

Regional classifications, such as the MLRAs and Hammond's land-form maps (Hammond 1964), have been integrated with the DDRP sites. These data are being used to examine regional controls or influences on surface water chemistry. For example, to analyse the relationship between hydrology and surface water chemistry, regional classifications are being used as a stratum for statistical analyses of geomorphic/hydrological parameters (e.g., drainage density) (Rochelle *et al.* 1989).

## 3. Spatial analyses

Two distinct characteristics of a GIS facilitate the analysis of spatial data. These are topological structure (e.g., spatial relatedness) and the incorporation of a database management system (DBMS) linked to unique spatial entities. Topological structure allows the examination of the spatial relationship between variables and facilitates processing of data using spatial criteria. For example, proximity analysis is facile on a GIS, in part because of the presence of topological structure. The linking of a DBMS and spatial entities allows assignment and processing of attribute information. This allows us to display and interpret the spatial trends of environmental data and the results of modelling.

Spatial analysis is primarily used in the DDRP to examine the processes and/or relationships that appear to influence or control acidification of surface waters. We do not use a GIS to model processes. Rather, we use the GIS in conjunction with existing watershed models and statistical procedures. The GIS is typically used either to develop data sets for modelling/statistical use or to display results obtained from the model. In this respect, the GIS is one of a series of tools that are used within the DDRP for the analysis and interpretation of environmental data.

### 3.1. *Large-scale spatial analysis*

In order to examine the relationships of mapped characteristics to surface water chemistry, the GIS is used to produce statistical summaries of land area (e.g., area in a soil type, forested versus non-forested) within the study watersheds. The resulting data files are used in statistical analyses to examine possible associations between land area data and surface water chemistry. Certain land types, however, may exert a disproportionate influence on the chemistry of surface water. For example, a wetland located directly where a major tributary enters a lake might act to control the chemistry of the lake more than a wetland situated near the drainage divide. We used proximity to the lake or stream to define the role of proximal land units on the chemistry of surface water.

For stream/watershed systems (Mid-Appalachian Region and Southern Blue Ridge Province), proximity was defined on the basis of linear distances. Buffers of 30 m and 100 m around perennial streams were generated with the GIS. These distances generally are large enough to include any of the major riparian zones within the

watershed. The buffers were then used to clip the other layers (e.g. soils) and statistical summaries of the resulting land area were generated.

Unlike the Mid-Appalachian Region and Southern Blue Ridge Province, the more complex hydrology of the northeastern lake/watershed systems required a different approach. First, GIS-generated linear buffers of 30 m and 100 m around the sampled lake were examined for relationships to surface water chemistry. Although some significant relationships were found, much of the potentially significant hydrologically- and chemically-active land areas were not included within the buffer zone. To include these active areas in the analysis, elevational buffers (defined as the area surrounding the study lake that is bounded by a selected elevational contour) were generated. Elevational buffers differ from linear buffers in two ways: (1) low-lying, hydrologically active areas (e.g., wetlands) are better represented, and (2) steeper areas around the lake are less well represented.

An example of the effect of using elevational buffers is shown for Long Pond, New Hampshire (figure 3). For this watershed, wetlands comprise 36 per cent of the land area within the elevational buffer, versus only 7 per cent of the land area for the watershed as a whole. The dominance of wetlands within the elevational buffer is also reflected in high values of two indicators of the organic content of surface water: colour and dissolved organic carbon (DOC). Measured values of colour and DOC for Long Pond place it in approximately the ninetieth percentile of the NSWS-defined population with regard to those characteristics.

The GIS also provides sufficient tools to integrate watershed characteristics vertically. For example, an overlay of soils and depth to bedrock has allowed a more complete characterization of soils with regard to depth to bedrock. Eventually, overlay capabilities will allow us to examine more fully the association among different watershed characteristics.

### 3.2. *Small-scale spatial analysis*

The GIS can facilitate spatial analysis of regional environmental data. For example, the spatial patterns of ANC within Adirondack State Park, New York, can be displayed and interpreted efficiently with the aid of GIS-generated circle maps (figure 4). Small-scale spatial analysis has also proved useful for examining the comparability of different sources of environmental data.

The GIS also allows easy visual examination of several environmental variables at the same time. For example, one critical question being addressed involves identifying the relationship between deposition of atmospheric sulphur and concentrations of surface water sulphate. This can be examined graphically (figure 5) (Sullivan *et al.* 1988), or spatially using the GIS (figure 6). The relationship between deposition of atmospheric sulphur and concentrations of surface water sulphate is apparent. As a second example, median sulphur retention (an important environmental measure of the amount of atmospherically-deposited sulphur retained within a watershed (Rochelle *et al.* 1987, Rochelle and Church 1987)) within MLRA regions is being evaluated for regional patterns (figure 7). Although statistical analyses can be used to indicate significant differences between regions, the GIS allows us to see relationships and examine patterns more easily. The ability of a GIS to display efficiently these types of results is critical for other types of analyses as well. In particular, we can display and interpret interactively the spatial trends of the results of modelling for alternative scenarios of atmospheric deposition. The usefulness of a GIS in these types of analyses is clearly evident.

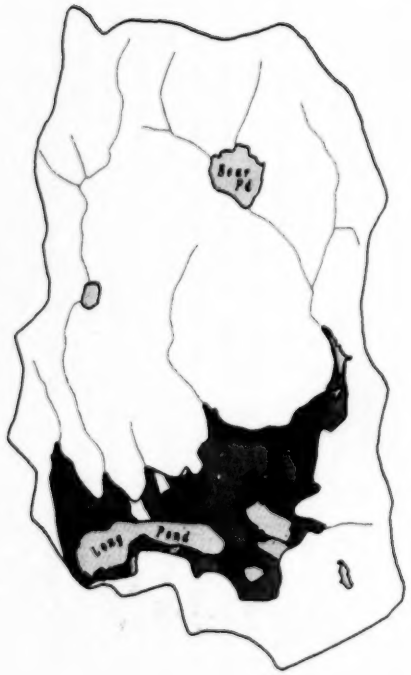

Figure 3. An example of the use of elevational buffers in lake/watershed systems. Land use within the first 40′ elevational contour—Long Pond, New Hampshire.

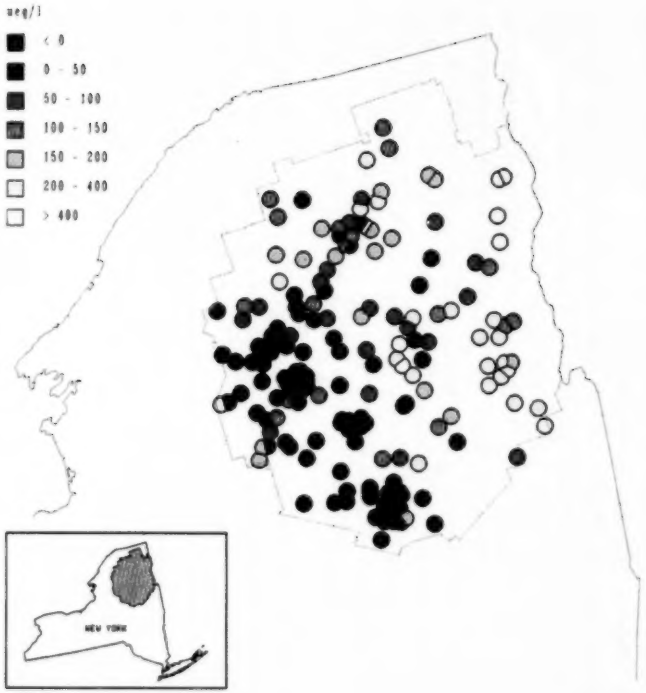


Figure 4. ANC for National Surface Water Survey sites in Adirondack State Park, New York (location map inset). (Source of data is Linthurst *et al.* 1986.)

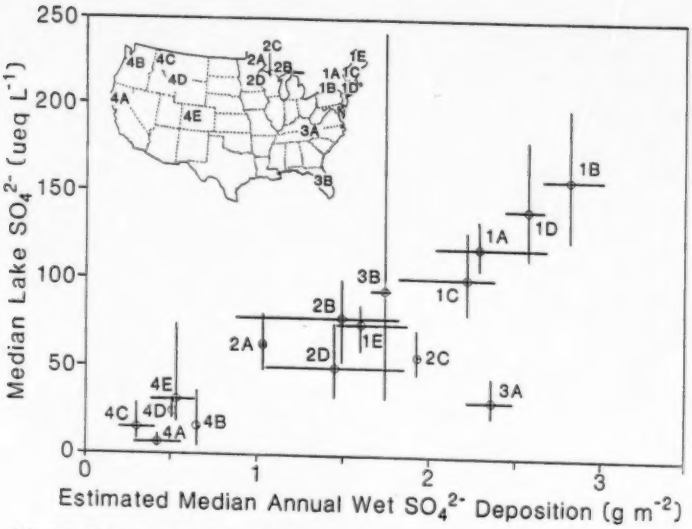


Figure 5. Median (circle) and twenty-fifth and seventy-fifth percentiles (bars) of measured lake sulphate as a function of wet sulphate deposition for sub-regions of the National Surface Water Survey (Sullivan *et al.* 1988). Reprinted by permission from *Nature*, Vol. 331, p. 607, copyright © 1988 Macmillan Journals Limited.

## 4. Communication of results

Maps can be an effective tool for communicating important environmental findings obtained from a regionally-based environmental study such as the DDRP. The GIS is a valuable tool in this regard as we can produce various types of mapped output efficiently.

As previously discussed, sulphur retention is one measure of the ability of a watershed to buffer against or delay acidification (figure 7). Sulphur retention can also be combined mathematically with ANC (calculated as the difference between theoretical steady-state surface water sulphate concentration and current sulphate concentration, divided by ANC (Church *et al.* 1989)) to generate an index of potential acidification. The index is directly related to the amount of sulphate that can be adsorbed by the watershed before reaching steady-state (i.e., inputs = outputs) and is inversely related to the ability of the watershed to neutralize incoming (atmospheric) acidic deposition. The index values were computed for the NSWS sites and summary statistics were compiled within MLRA regions. The same data can also be displayed in map form (figure 8). The map clearly shows regions of the eastern U.S. where the potential for acidification of surface water might be greatest. The results of the index calculations could have important policy implications. The value of a GIS is that we can easily produce the same type of map using alternative scenarios of deposition.

## 5. Summary

The DDRP is a project of regional, national and international importance. Results obtained from the DDRP are likely to have significant influence over legislative actions pertaining to sulphur emissions in the United States. We incorporated a GIS into the DDRP to perform a variety of functions. While some functions were simply locational

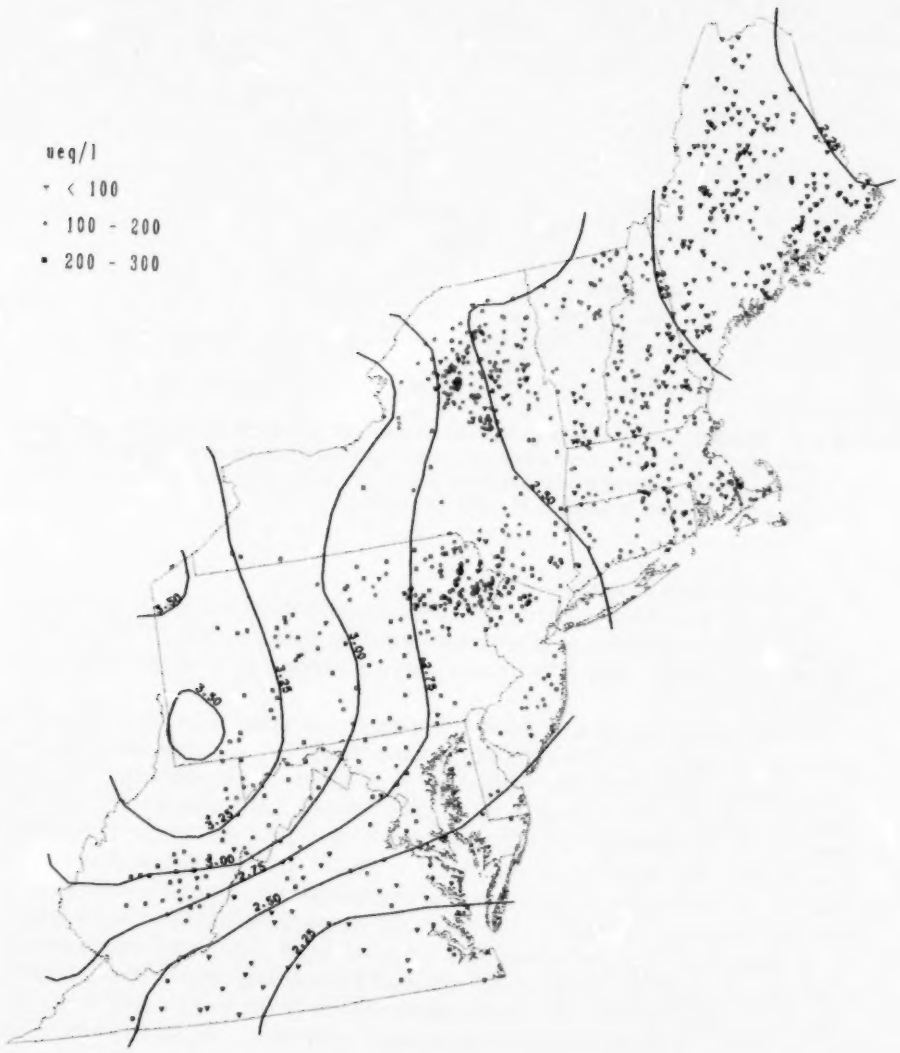


Figure 6. Lake and stream sulphate concentration and wet deposition contours ($g/m^2$) for National Surface Water Survey sites.

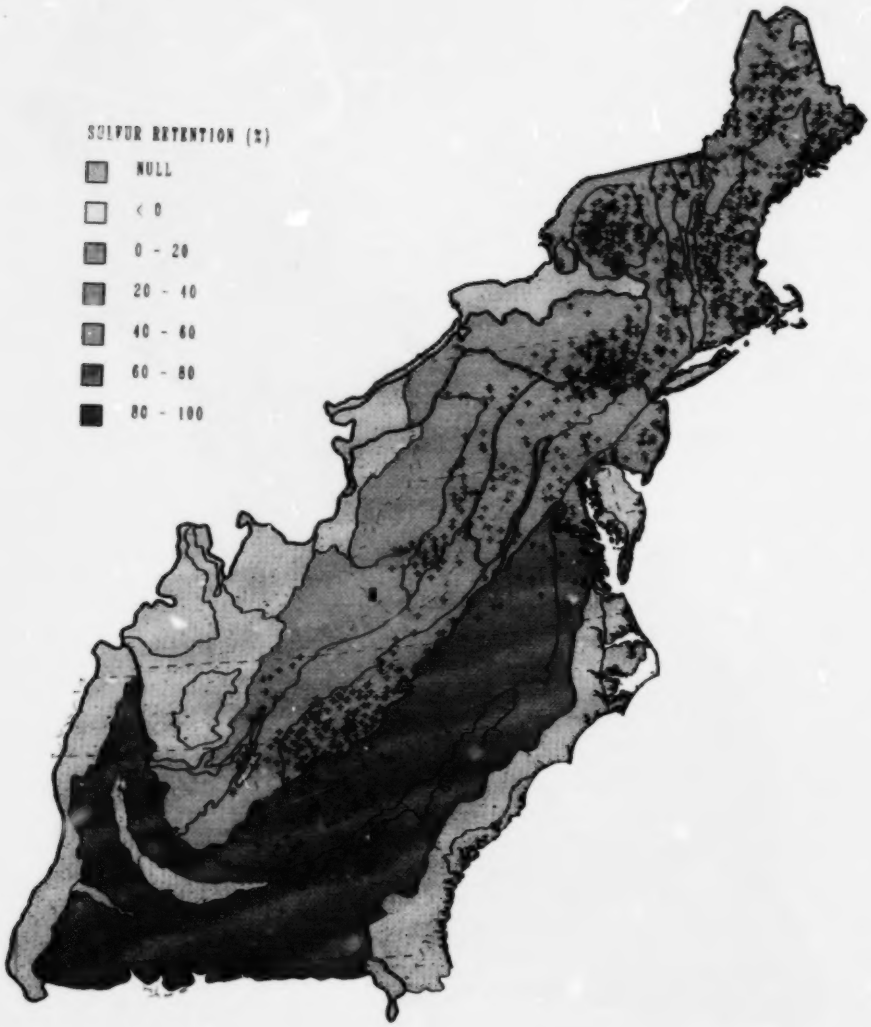


Figure 7. Median percentage sulphur retention within MLRA regions. Grey areas indicate regions of little or no data. Crosses are NSWS sites ($n = 1291$).

Figure 8. Median index of potential acidification within MLRA regions. Sites with ANC > 200 $\mu$eq/l or sulphate > 400 $\mu$eq/l were eliminated. Grey areas indicate regions of little or no data. Crosses are NSWS sites.

or logistical, two primary functions were of critical importance to the successful completion of the DDRP.

First, we used a GIS to characterize the study watersheds by aggregating, managing and processing numerous sources of mapped and other environmental data. This characterization was critical as the success of the DDRP was largely dependent on the ability to characterize the regions under study adequately. Second, because a GIS is an efficient tool for producing maps, we were able to display and analyse spatial patterns of chemical variables, the results of modelling and other data relevant to the effects of acidic deposition, with ease. This assisted us in analysing regional data that could influence or control the effects of acidic deposition. Additionally, we could interpret efficiently the spatial patterns of modelling using different assumptions in the model and alternative scenarios of atmospheric deposition.

We believe that these GIS capabilities have enabled us to address more adequately the long-term effects of acidic deposition on aquatic systems. These capabilities have increased the defensibility, timeliness and validity of results obtained in the DDRP. Ultimately, this should translate into a stronger scientific basis for policy decisions regarding the emissions of sulphur in the United States.

**Acknowledgments**

J. Omernik first recognized the need and was responsible for obtaining a GIS for research within the laboratory. We commend him for his foresight and thank him for his assistance in making the system a reality. We thank A. Herstrom, A. Kinney and D. Nesbitt for their work in establishing, managing and maintaining the GIS, and C. Kaffke for assisting in its development within our project. We thank T. Sullivan and the editors of *Nature* for their permission to reproduce figure 5. Our thanks also go to B. Rochelle, P. Shaffer and C. Liff for their help in processing data presented here. Finally, we are grateful B. Rochelle, D. Coffey, A. Hairston, D. Landers, C. Savonen and D. White for providing very helpful reviews of this manuscript. This research is part of the Direct/Delayed Response Project, part of the National Acid Precipitation Assessment Program.

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